NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4094

EFFECTS OF EXTREME SURFACE COOLING ON BOUNDARY-LAYER TRANSITION

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SUMMARY

An investigation was made to determine the combined effects of surface cooling, pressure gradients, nose blunting, and surface finish on boundary-layer transition. Data were obtained for various body shapes at a Mach number of 3.12 and Reynolds numbers per foot as high as 15×10^6.

Previous transition studies, with moderate cooling, have shown agreement with the predictions of stability theory. For surface roughnesses ranging from 4 to 1250 microinches the location of transition was unaffected with moderate cooling. With extreme cooling, an adverse effect was observed for each of the parameters investigated. In general, the transition Reynolds number decreased with decreasing surface temperature. In particular, the beneficial effects of a favorable pressure gradient obtained with moderate cooling disappear with extreme cooling, and a transition Reynolds number lower than that observed on a cone is obtained. Further, an increase in the nose bluntness decreased the transition Reynolds number under conditions of extreme cooling.

INTRODUCTION

The ability to maintain a laminar boundary layer on a supersonic vehicle is of major importance in lessening aerodynamic heating. Theoretical studies of laminar-boundary-layer stability have pointed out the possibility of delaying the onset of transition on a flat plate by cooling (e.g., ref. 1). Investigations conducted with cones and other bodies of revolution, reported in references 2 to 5, indicate that transition can be delayed by surface cooling, by using shapes with favorable pressure gradients and by blunting leading edges.

[1]Paper presented at Symposium on High-Speed Aerodynamics and Structures, Gainesville, Florida, Jan. 22-24, 1957.

However, in reference 3, under one condition early transition was reported on the favorable-pressure-gradient model and was thought to be a result of some extraneous effect such as tunnel disturbances or a local surface abrasion. A more recent investigation on the effects of cooling and nose blunting (ref. 5) reported startling effects for extreme surface cooling and offered further evidence of the early transition reported in reference 3. The investigation presented in reference 5 indicated that the expected transition delay for cooling and blunting a cone tip is found for moderately cooled surfaces. However, if the surface is cooled below a certain temperature ratio (referred to as extreme cooling), an adverse effect is noted and the Reynolds numbers of transition are of the same order as those experienced without cooling. This reappearance of low transition Reynolds numbers with extreme cooling is termed "transition reversal."

The purposes of the present report are to present experimentally observed effects of various factors which affect or are related to transition reversal and to discuss possible explanations for their causes. Tests have been conducted on bodies of various shapes with surface finishes ranging from 4 to 1250 microinches in the same Mach number 3.12 facility discussed in reference 3.

APPARATUS AND PROCEDURE

Tests were conducted at a Mach number of 3.12 in the 1- by 1-foot variable Reynolds number supersonic wind tunnel at the NACA Lewis laboratory. The stagnation temperature of the inlet air (50° to 170° F) and the inlet pressure were varied to yield free-stream Reynolds numbers per foot up to 15×10^{6}. The tunnel dewpoint was about -35° F at all times.

The experimental setup, including tunnel mounting, and test procedure were the same as those described in reference 6. The configurations tested were precooled by liquid nitrogen to approximately 120° R (-340° F), and transient temperature distributions were obtained using a multiple-channel recording oscillograph. Reference 3 gives a more detailed description of the transient technique used. A typical model installation in the wind tunnel is shown in figure 1.

Sketches of the models investigated and their instrumentation schedules are presented in figure 2. The cone-cylinder model was fabricated from monel, whereas all other test configurations were made of "K" monel. All models were constructed with a nominal wall thickness of 1/16 inch with the exception of the 120°-cone-cylinder, which had a wall thickness of 1/20 inch. The blunt cone-cylinder was obtained by cutting 1 inch off the sharp cone-cylinder and blunting the tip to a 3/32-inch radius. Thermocouple locations for this model are those for the sharp cone-cylinder model minus 1 inch.

The following table presents the models tested and the surface finishes used:

Model	Surface finish	Average roughness height, microin.
Sharp cone-cylinder	Smooth	12
Sharp parabolic-nosed-cylinder	Smooth	<16
Blunt cone-cylinder	Smooth	12
Blunt cone-cylinder	Sand paper	38
Blunt cone-cylinder	Sand blasted	50
Blunt cone-cylinder	Sand blasted	100
Blunt cone-cylinder	Carborundum grit	500
Blunt cone-cylinder	Carborundum grit	1250
Hemisphere-cone-cylinder	Smooth	<16
Hemisphere-cone-cylinder	Sand blasted	130
120°-Cone-cylinder	Smooth	< 4

The average roughness heights of the metal surfaces were measured by a Brush surface indicator. No attempt was made to measure the Carborundum grit finishes. Here the average particle size was arbitrarily picked as an indication of the roughness height. The Carborundum coatings were applied to a very thin uniform coating of adhesive and were examined for uniformity with a microscope. The Carborundum finishes were uniform, and their reproducibility was good. All smooth surfaces were obtained by machine-polishing with the exception of the 4-microinch finish on the 120°-cone-cylinder. This surface was obtained by hand-polishing using a commercially available diamond rubbing compound.

In the present investigation, two methods of choosing the location of transition were used. First, from plots of heat-transfer coefficient against Reynolds number, transition was chosen as that point where the coefficient began to increase above the laminar value. The second technique was choosing the transition location directly from oscillograph traces of temperature against time. Here, a sudden change in the slope of a trace was identified with the sudden change in heat-transfer coefficient associated with transition. Since both methods agreed very closely, the majority of the transition data were obtained by the second method. The selection of the transition location, as defined herein, was consistent to within 1/3 inch on the models tested.

Because the models were cooled to -340° F, air components such as oxygen, carbon dioxide, and water vapor could condense on the cold surfaces and thereby generate a surface roughness that could contribute to early transition. In fact, as the surface temperature increased, two condensation films were observed to form and evaporate in a number of tests (ref. 6). In spite of the fact that the condensation film increased in extent and thickness, the amount of laminar flow increased considerably. Furthermore, transition reversal has been observed both with and without the condensation films and at various temperature levels depending on model geometry and surface roughness. Consequently, it was concluded that the observed condensation films did not cause the reversal phenomenon. 4380

RESULTS AND DISCUSSION

Effect of Extreme Cooling

According to stability theory, reducing the surface temperature of a model should increase the length of laminar run. In fact, theoretical analyses suggest that by removing a sufficient amount of heat the boundary layer would be stabilized to very high Reynolds numbers. The effect of moderate cooling has been found to be in qualitative agreement with the trend predicted by stability theory. However, with extreme cooling, transition results have been obtained that are not compatible with the basic trend predicted by stability theory. A typical set of data showing the effects of cooling a sharp-tipped cone-cylinder model having a surface finish of 12 microinches is presented in figure 3. The data are presented in terms of the ratio of wall to adiabatic wall temperature at transition $(T_w/T_{ad})_{tr}$, and the transition Reynolds number (Re_{tr}) based on free-stream properties.[2] The temperature ratios range from 1.0, which represents the insulated wall temperature, to 0.25, which represents a surface temperature of approximately -340° F (120° R).

As shown in figure 3, two distinct curves are obtained over the cooling range. For moderate amounts of cooling, the results conform to the trend suggested by stability theory. However, with extreme cooling, the transition Reynolds number decreased with decreasing temperature level. As a consequence of this transition reversal, the flow on a portion of a model subjected to aerodynamic heating may initially be turbulent, then laminar, and finally turbulent. This phenomenon noted in reference 3 was, at the time, attributed to tunnel disturbances or local surface abrasions because of insufficient evidence. Later, Van Driest and Boison (ref. 7) observed reversal on a cooled cone with single roughness elements and attributed the phenomenon to the roughness elements. However, the observation of transition reversal for a model having a 12-microinch surface finish was unexpected. Subsequently, reversal was found on many different shaped bodies having surface finishes ranging from 2 to 1250 microinches. In addition, the complete cycle of this phenomenon has

[2]The use of the adiabatic wall temperature as a reference does not imply that it is a significant temperature for correlating the data. It is, however, a convenient means of defining a temperature ratio.

been recorded by motion pictures obtained through a magnified schlieren system. The transition results obtained in this manner agree with those obtained from the oscillograph traces. As a result, there is little doubt that this phenomenon actually exists.

Initially many ideas were advanced concerning the cause of reversal. One of these ideas attached significance to the adverse pressure gradients found on all the models at various axial locations. However, reversal data have been obtained with and without adverse pressure gradients (fig. 3). Another proposal was that, if all the fluid properties were evaluated in terms of local wall conditions, reversal might be eliminated. The modified plots still showed the presence of reversal. In addition, the question was raised as to whether or not reversal could be attributed to tunnel disturbances. However, transition reversal did not occur at fixed locations as might be expected with finite tunnel disturbances. Finally, attention was focused on surface roughness as the parameter causing reversal. The argument was that sufficient cooling decreased the boundary-layer thickness δ so that a given surface roughness h was large enough to cause early transition. On the other hand, if reversal is assumed to exist for a hypothetically smooth model, it is expected that transition would be advanced by increases in roughness size in the manner observed experimentally; hence, the reversal phenomenon is not necessarily due to roughness. A consequence of the above arguments is that of all the explanations of reversal proposed no one explanation has been completely satisfactory.

The effects of various factors on transition and specifically on the transition reversal phenomenon obtained with extreme cooling are now considered.

Effect of Pressure Gradient

The combined effects of cooling and a favorable pressure gradient are shown in figure 4. The data for this figure were obtained from the sharp-tipped parabolic-nosed-cylinder model, which has a favorable pressure gradient on the nose section. Again, the data are presented in terms of the ratio of wall to adiabatic wall temperature, and transition Reynolds number. For reference purposes, curves faired through the data for the sharp-tipped cone are presented. For moderate cooling, the parabolic model has a transition Reynolds number about twice that of the sharp-tipped cone. This has been attributed to the favorable pressure gradient existing on the nose and is in agreement with the trend predicted by stability theory. However, with extreme cooling the reverse occurs; the transition Reynolds numbers for the parabolic model are considerably less than those obtained from the sharp-cone configuration. This behavior tends to support the roughness argument, since the boundary layer is thinned not only by cooling but also by the favorable pressure gradient. Hence, the ratio of roughness height to boundary-layer thickness $\frac{h}{\delta}$ becomes critical sooner than does that for the sharp-tipped cone.

For a time, it was thought that boundary-layer instability could arise under conditions of extreme cooling because of body curvature. Recently, Lees (ref. 8) and Lessen (ref. 9) have considered the effects of surface curvature on the stability of the boundary layer. The derived stability equations indicate that, under conditions of extreme surface cooling, a large density gradient normal to the surface may lead to vortex instability. Lees, however, further shows that with convex streamline curvature and extreme surface cooling the boundary layer is always stable.

Effect of Blunting

The effect of blunting the cone-cylinder model to a tip radius of 3/32 inch is shown in figure 5. Blunt leading edges produce lower local Mach numbers and Reynolds numbers adjacent to the body than are obtained with sharp leading edges (refs. 4 and 10). Hence, transition on the blunted cone should be downstream of the location noted for the sharp-tipped cone. As observed in figure 5, this actually is the case with moderate cooling. Under extreme cooling conditions, however, the blunt-model data are almost coincident with the sharp-cone data obtained with the same flow conditions. The agreement may be coincidental, or it may mean that the reversal phenomenon is insensitive to local Reynolds number. The above comparison cannot be made for a unit Reynolds number per foot of 10.9×10^6 because sharp-tip data were not obtained for this Reynolds number.

Figure 6 shows transition results obtained from the original cone-cylinder model spherically blunted to a tip radius of 0.7 inch. Under equilibrium conditions and also with moderate cooling, the transition point is beyond the last thermocouple on the model so that the transition Reynolds number is at least 4×10^6. With additional cooling, transition is observed to move upstream towards the tip. At no time with cooling was transition observed on the spherical tip. A comparison of these data with those from the sharp-tip configuration shows that large blunt leading edges have an adverse effect under conditions of extreme cooling. Figure 6 also shows that increasing the unit Reynolds number in the reversal region decreases the transition Reynolds number.

Another blunt body tested was a cone-cylinder having a cone included angle of 120°. The data for this model are presented in figure 7. The cone angle used is such that a detached shock was obtained ahead of the model. Unlike the results obtained from the cone blunted to a 0.7-inch tip radius, these data actually show the point of transition reversal. That is, at thermocouple locations downstream of the points showing reversal the flow is turbulent at all times. All the data presented in figure 7 were obtained on the cylindrical portion of the model. In addition, a comparison of these data with those presented in figure 6, shows that at a given temperature level in the reversal region the 120°-cone-cylinder has a longer laminar run.

Effect of Surface Roughness

Since the effects of roughness are mentioned several times, the question naturally arises as to the variation of reversal with roughness. Figure 8 shows data obtained from the 3/32-inch-radius blunted cone-cylinder at two unit Reynolds numbers per foot and for surface finishes ranging from 12 to 1250 microinches. These finishes were obtained by machine-polishing, sanding, sand-blasting, and by applying Carborundum grit. As shown in figure 8, the normal trend of the downstream movement of transition with cooling reverses at different temperature levels for each of the various surface finishes. The rougher surfaces experience reversal at higher surface temperatures, and consequently they have lower transition Reynolds numbers than the smooth surfaces. A comparison of the data obtained with the 500-microinch grit finish with the data from the 100-microinch metal finish indicates that the metal finish promotes earlier transition in the reversal region. Actually, this comparison probably means that the surface finishes obtained with Carborundum grit are not as rough as the grit size indicates. Up to the point of reversal, all the data fall on essentially one curve indicating that the effects of roughness are small for moderate cooling.

Transition data were also obtained for the hemispherically blunted model (tip radius, 0.7 in.) with a surface finish of 130 microinches. These data, with data for a surface finish of about 16 microinches, are presented in figure 9 for two unit Reynolds numbers. The effects of surface finish and unit Reynolds number are similar to those obtained for the model blunted to a tip radius of 3/32 inch.

Roughness as Cause of Transition Reversal

The arguments in favor of roughness as the cause of transition reversal are as follows: The data show that surface cooling, favorable pressure gradients, and blunt leading edges can contribute to early transition under certain conditions. Each of these parameters can be associated with the roughness argument if the effect of the parameter on the boundary-layer thickness is considered. For example, surface cooling and favorable pressure gradients both tend to thin the boundary layer. Consequently, for a given roughness, the ratio of roughness height to boundary-layer thickness h/δ is larger; and, therefore, any roughness effects should be felt sooner with cooling and a favorable pressure gradient. These trends are supported by the experimental results. In addition, blunting the nose of a body lowers the local Mach number in the region near the body surface, and past experiments have shown that single roughness elements are more effective at lower Mach numbers. Thus, for blunted bodies under extreme cooling conditions where the data show early transition, the combination of roughness and a thin boundary layer could have canceled the favorable effect expected from blunting. Furthermore, it is not too surprising that an increase in the unit Reynolds number or roughness height would decrease the transition Reynolds number in the reversal region.

Since the trends of the data obtained in the reversal region can be qualitatively explained in terms of roughness, it might be concluded that roughness is the cause of transition reversal. However, the fact that roughness aggravates transition reversal cannot be taken as evidence that roughness causes reversal, anymore than transition itself can be attributed solely to roughness. Furthermore, the boundary-layer thinning effect due to cooling and a favorable pressure gradient is not very large. Consequently, for a given surface roughness, the change in h/δ due to heating or cooling is small. It is difficult to see why small changes in h/δ due to low surface temperatures should produce large changes in the transition Reynolds number when large changes in h/δ due to change in surface roughness produce little effect. This is even more difficult to understand when it is considered that the boundary layer should be more stable to disturbances at the lower surface temperatures. Therefore, it appears that transition reversal cannot be attributed primarily to surface roughness.

CONCLUDING REMARKS

The data presented show that surface roughness, favorable pressure gradients, and blunt leading edges contribute to early transition under certain conditions of surface cooling. The trends of the data obtained under these conditions can be qualitatively explained in terms of the surface finish. However, this explanation of the cause of transition reversal is not completely satisfactory. Even though a complete explanation cannot be given at this time, the reversal problem must be considered and dealt with in the practical case. For, if a missile design depends heavily on cooling to achieve long laminar runs, the trajectory should, if possible, be chosen so as to avoid the temperature ratios associated with transition reversal.

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National Advisory Committee for Aeronautics
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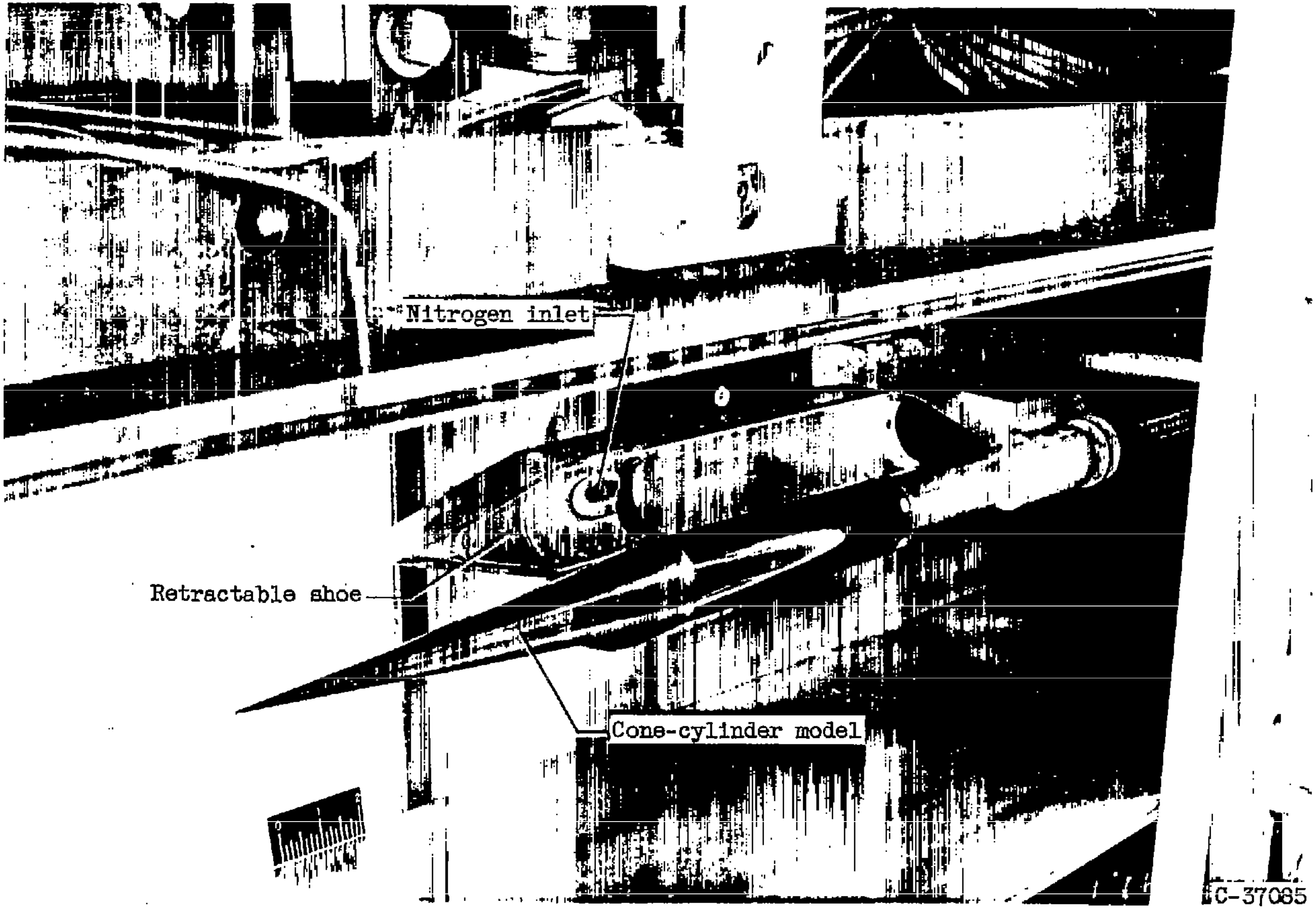
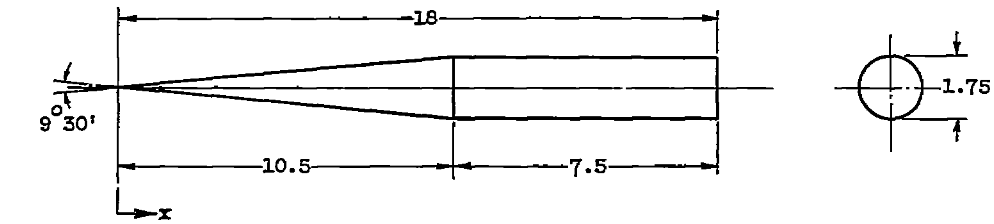
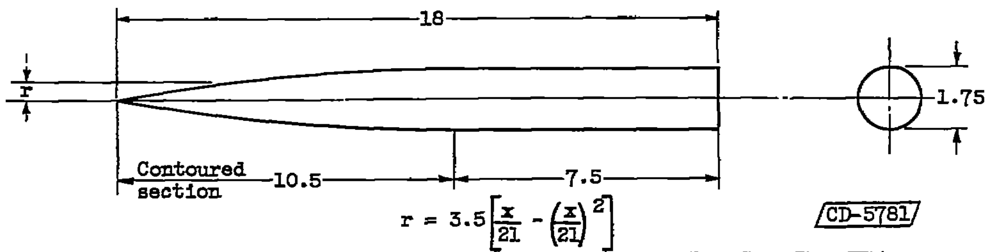


Figure 1. - Tunnel installation.



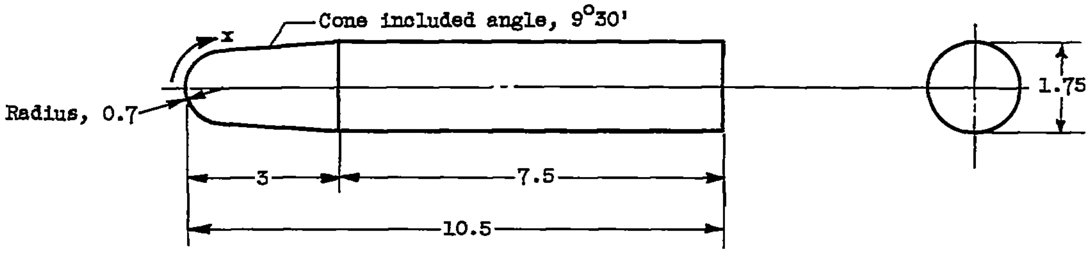
Thermocouple locations at axial distance x														
2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	10.62	11.50	12.50	13.62	14.75	16.00

(a) Sharp cone-cylinder.



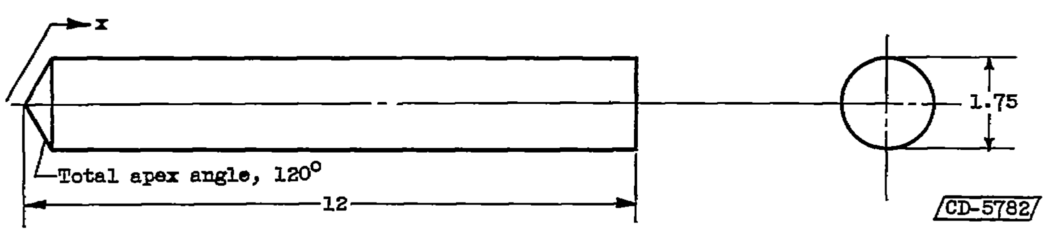
Thermocouple locations at axial distance x														
1.0	1.5	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.5	14.0	16.0

(b) Sharp parabolic-nosed-cylinder.



Thermocouple locations at generator distance x																		
0	.12	.23	.34	.45	.56	.67	.77	.88	1.06	1.44	1.94	2.94	3.55	4.43	5.43	6.55	7.67	8.92

(c) Hemisphere-cone-cylinder.



Thermocouple locations at generator distance x													
0	.19	.44	.69	.94	1.26	1.76	2.76	3.76	4.76	5.76	6.76	7.76	9.01

(d) 120° Cone-cylinder.

Figure 2. - Details of models and thermocouple locations. (Dimensions in inches.)

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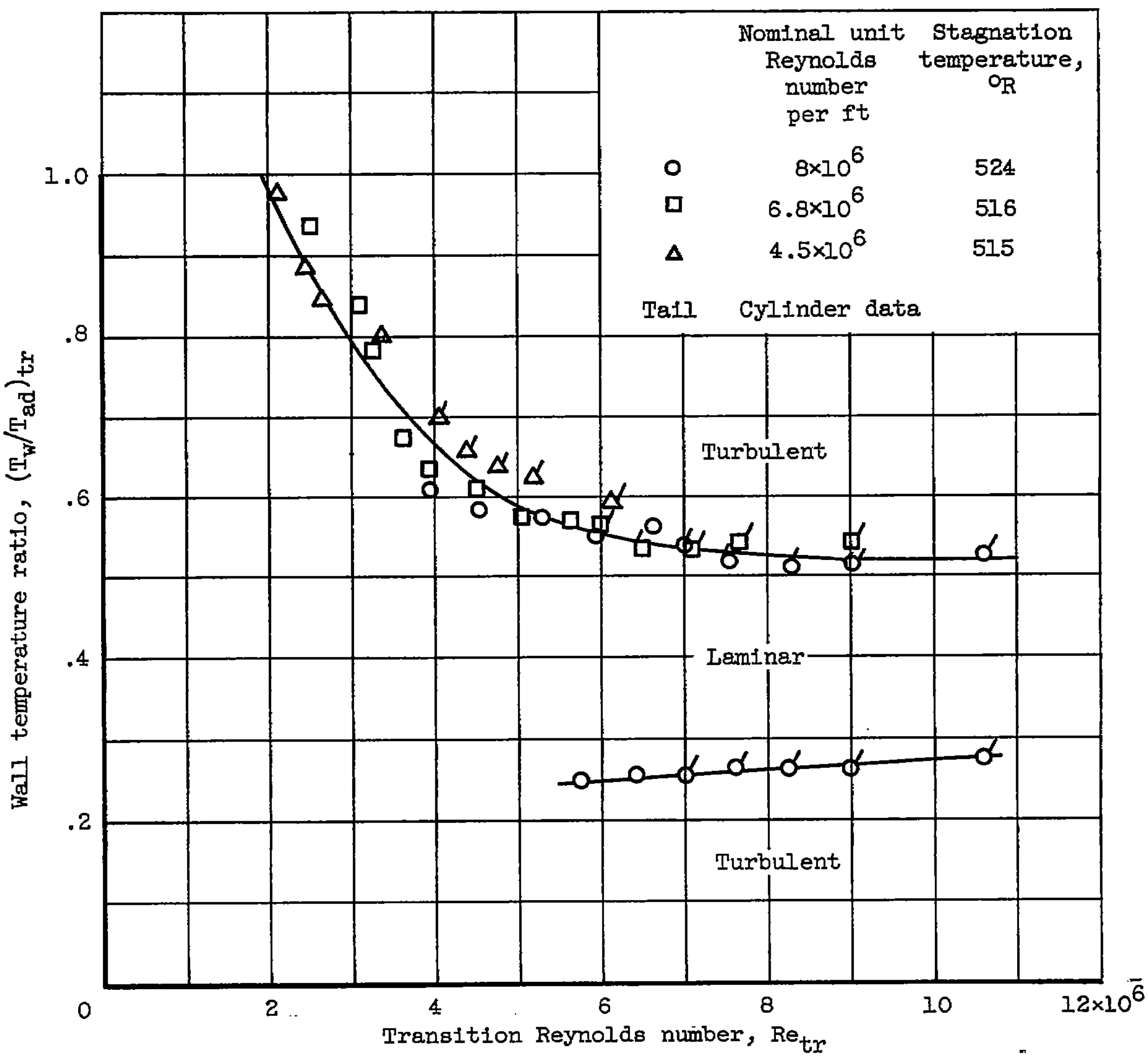

Figure 3. - Effect of surface cooling on boundary-layer transition. Sharp cone-cylinder; surface roughness, 12 microinches.

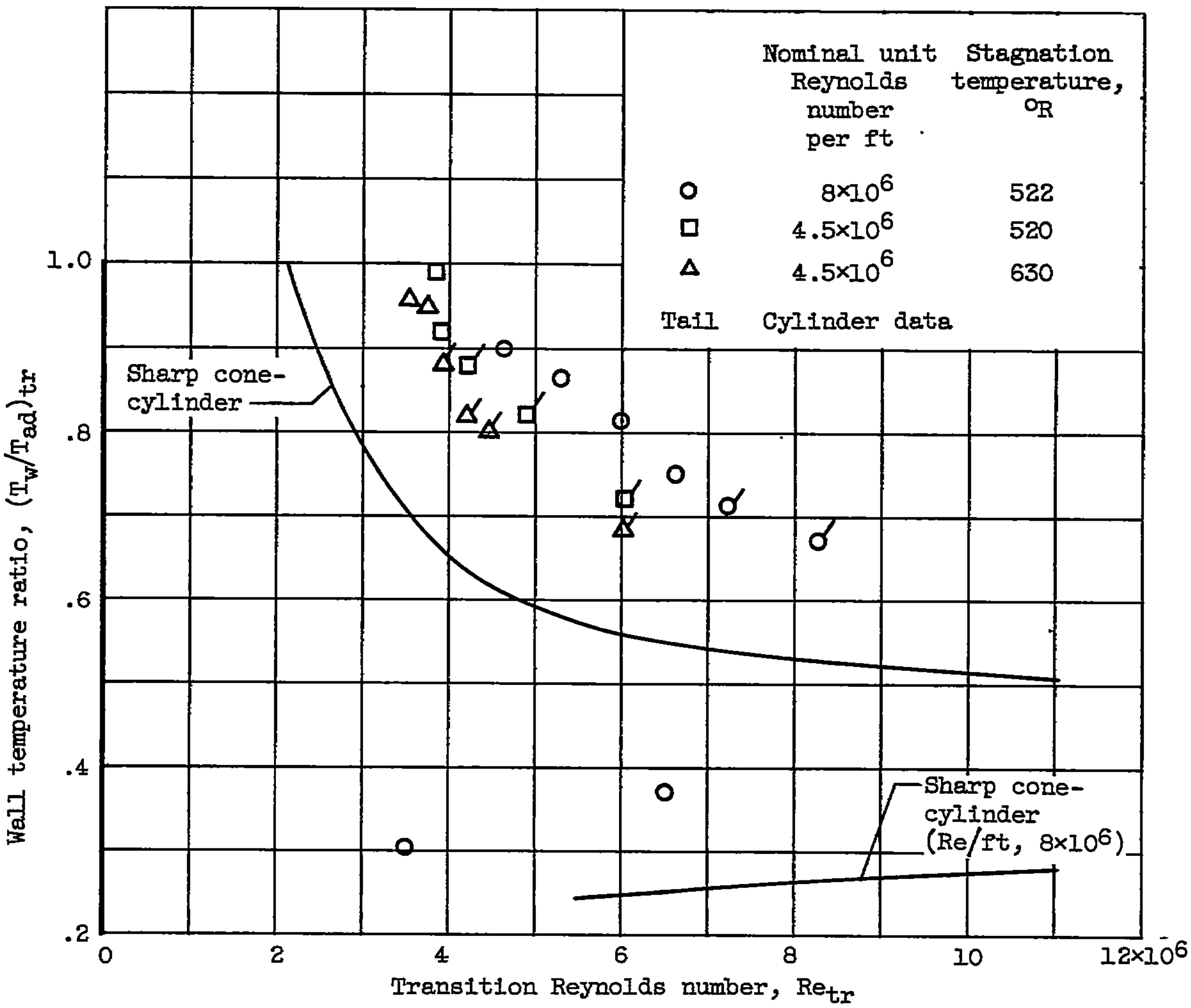

Figure 4. - Effect of cooling and pressure gradient on boundary-layer transition. Sharp parabolic-nosed-cylinder; surface roughness, <16 microinches.

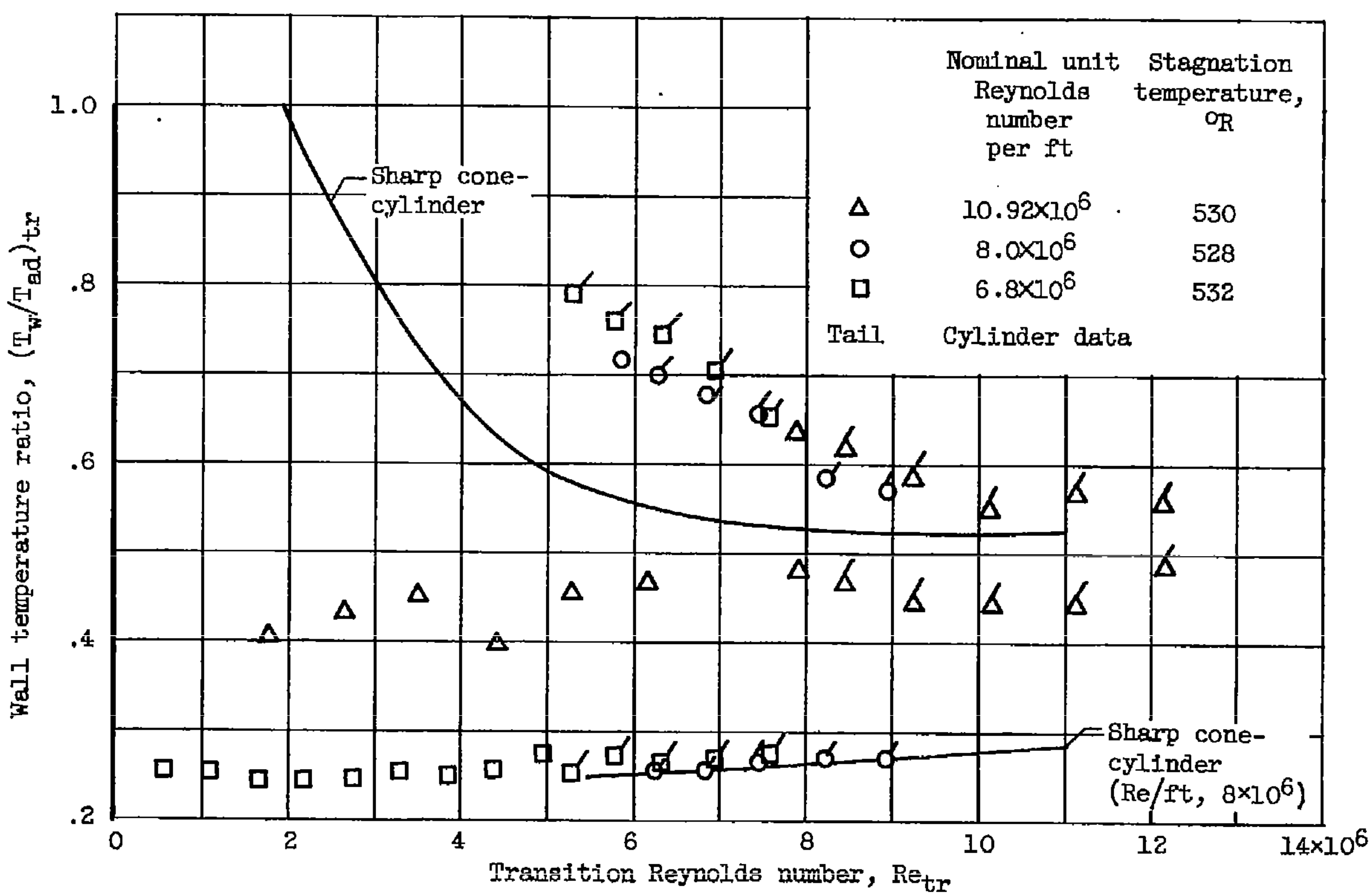

Figure 5. - Effect of cooling and blunting on boundary-layer transition. Spherically blunted cone; tip radius, 3/32 inch; surface roughness, 12 microinches.

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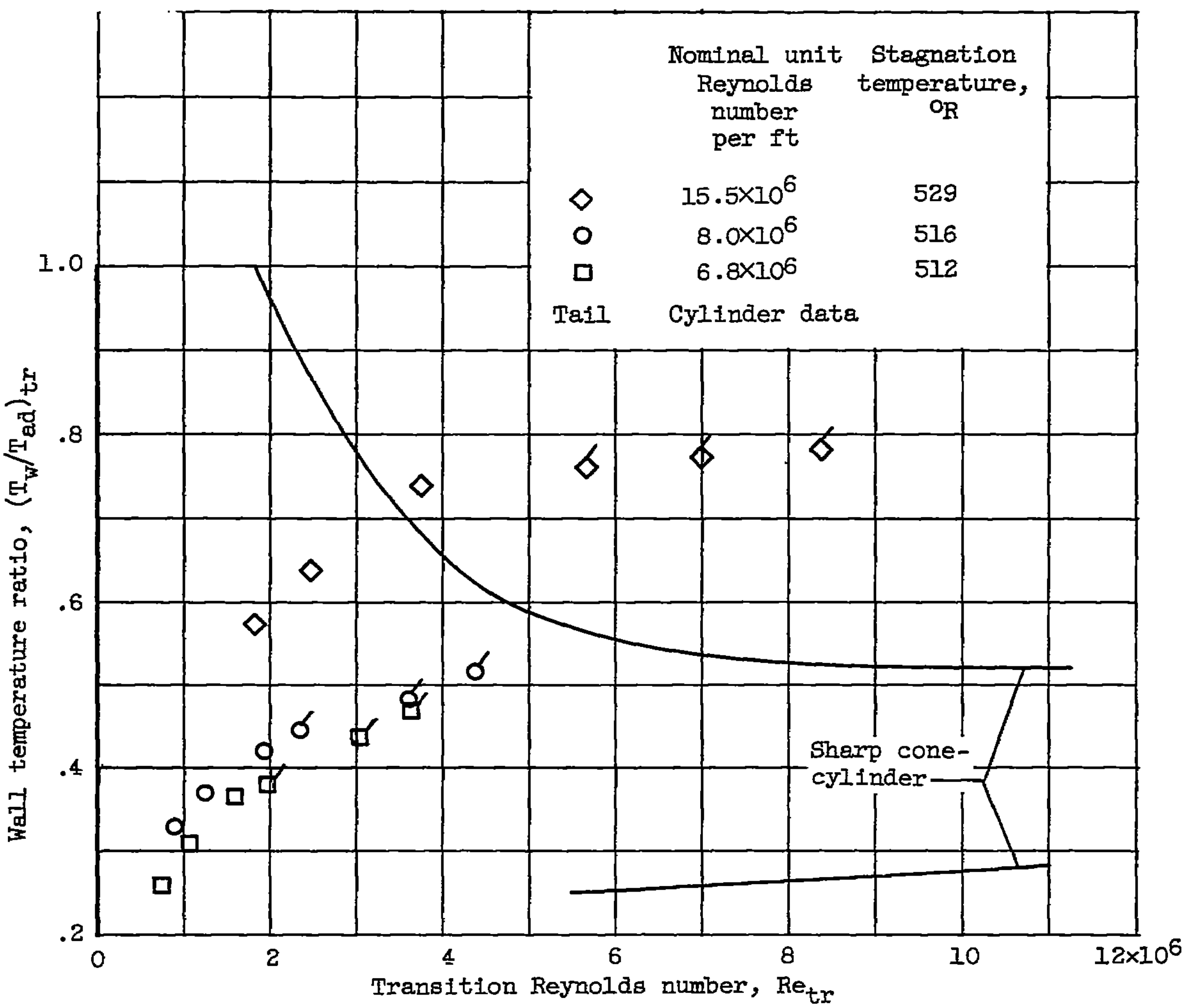

Figure 6. - Effect of cooling and blunting on boundary-layer transition. Spherically blunted cone; tip radius, 0.7 inch; surface roughness, <16 microinches.

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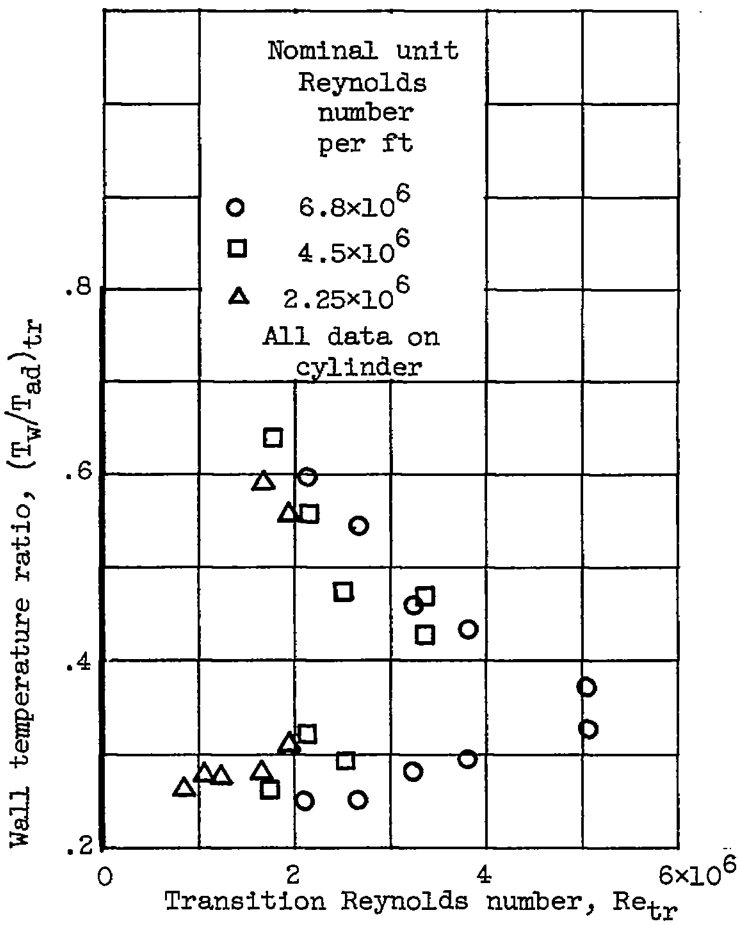
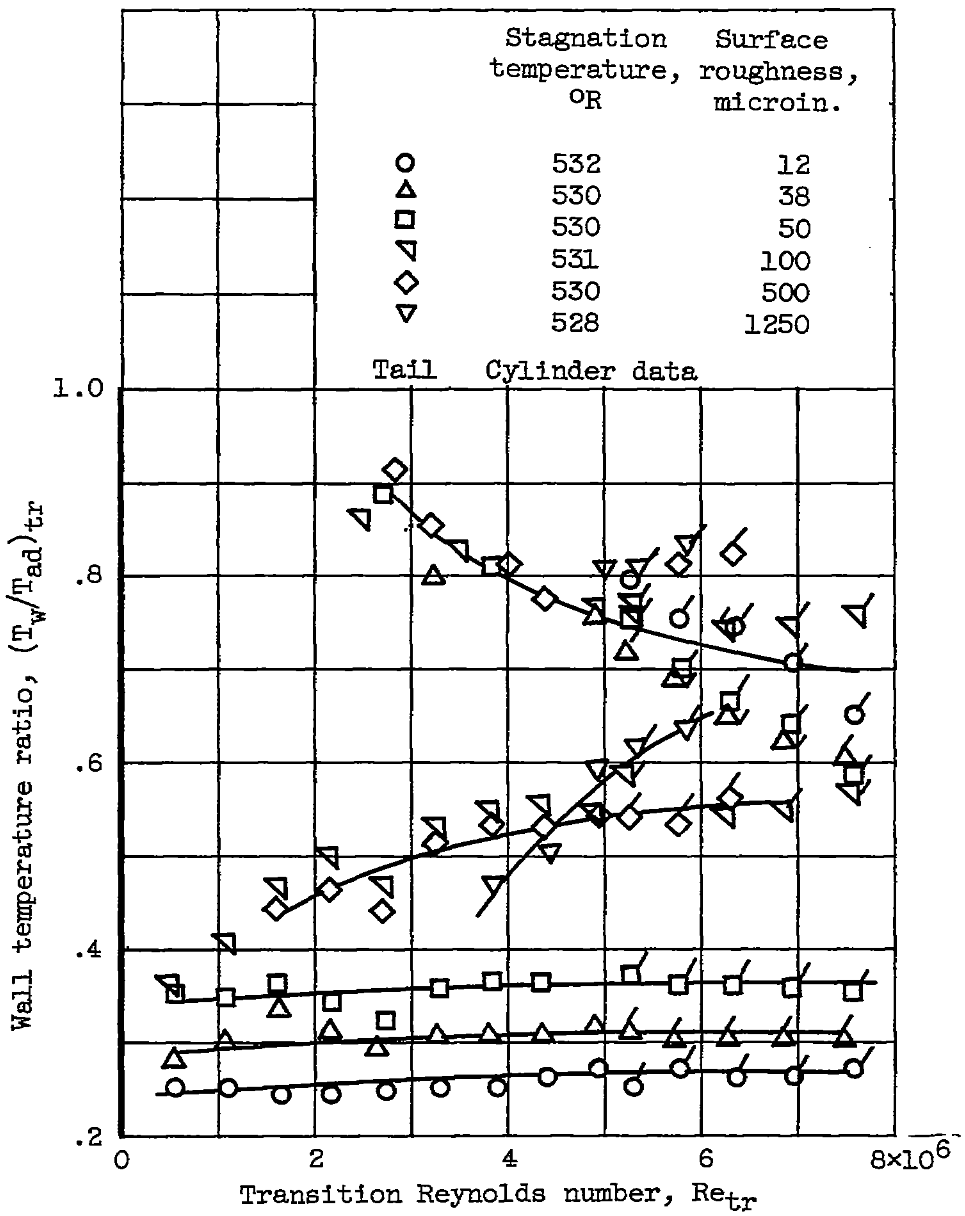
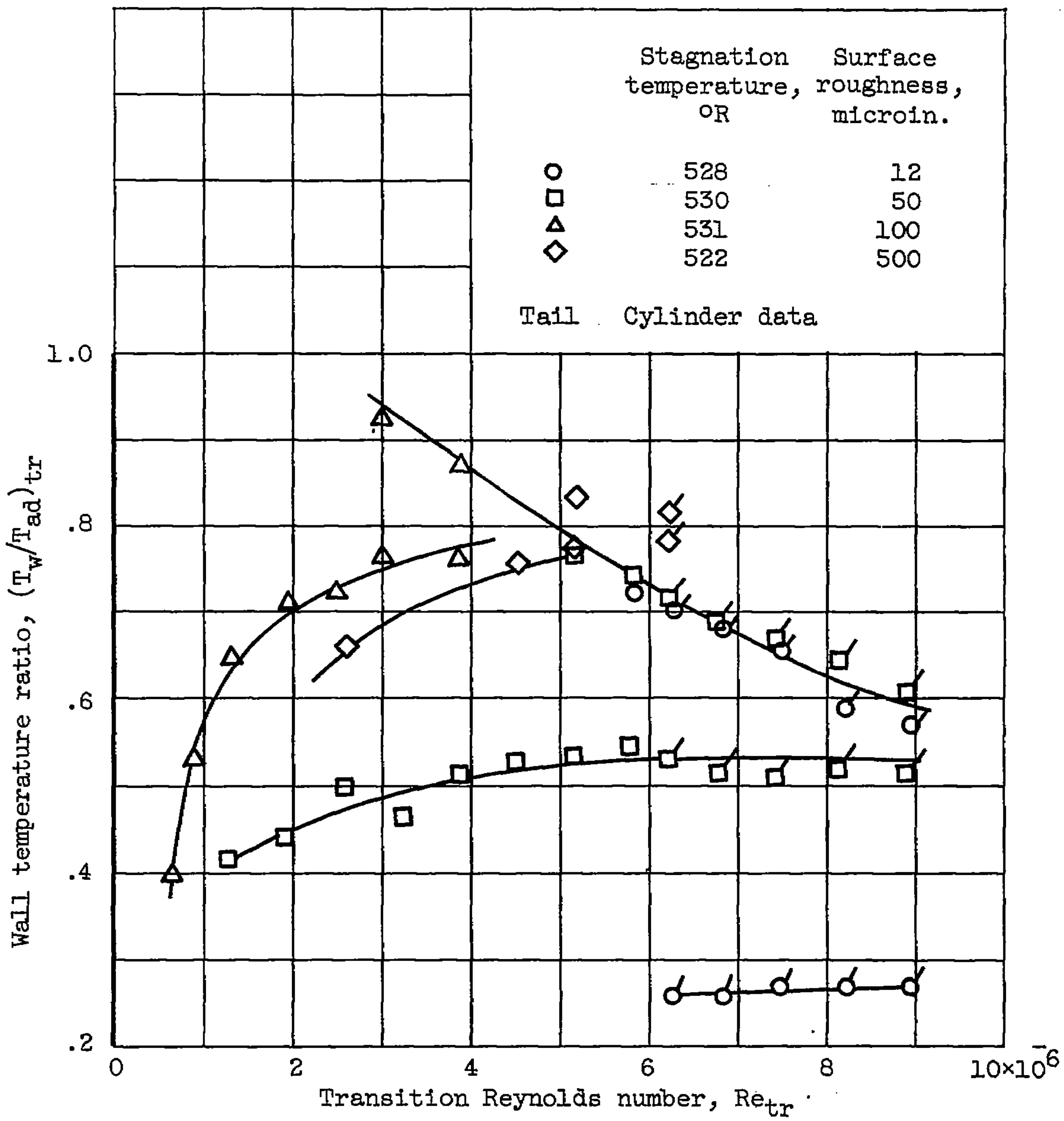


Figure 7. - Effect of cooling on boundary-layer transition. 120°-Cone-cylinder; surface roughness, <4 microinches; stagnation temperature, 530° R.



(a) Nominal unit Reynolds number per foot, 6.75×10^6.

Figure 8. - Effect of cooling and roughness on boundary-layer transition. Spherically blunted cone; tip radius, 3/32 inch.



(b) Nominal unit Reynolds number per foot, 8×10^6.

Figure 8. - Concluded. Effect of cooling and roughness on boundary-layer transition. Spherically blunted cone; tip radius, 3/32 inch.

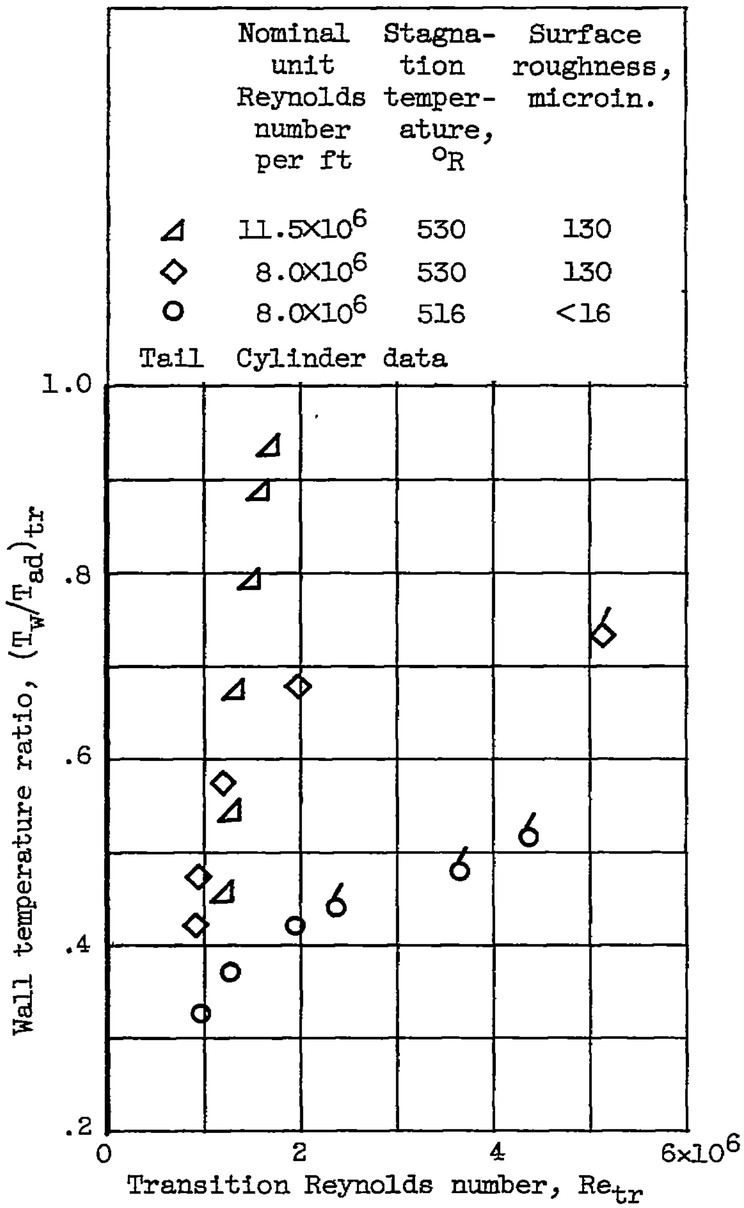


Figure 9. - Effect of cooling and roughness on boundary-layer transition. Spherically blunted cone; tip radius, 0.7 inch.